CHAPTER 5

OCEAN AND ICE IN THE EARTH SYSTEM

5.0 INTRODUCTION

The Earth's oceans and ice masses affect many facets of human life from the viability of coastal communities and ocean trade to climate conditions well within the interior of continents. During the last two centuries, mountain glaciers have been retreating in alpine valleys, sea level has risen by tens of centimeters and global-mean surface temperature has warmed substantially (the latter trend resuming in the early 1970's after a thirty year pause). In recent years, two of the largest El Niño events of the century have caused considerable disruptions and have been the focus of much public attention. Climate, including the ocean and ice environments, is no longer perceived as a static property of the environment, but is now viewed as having a dynamic state that is expected to evolve in the future.

Climate changes that occur over periods of years, decades or longer combine natural variability with the Earth system's response to changes in external forcings such as radiation from the Sun and, in recent times, disturbances by human activities, e. g. the increasing concentration of carbon dioxide in the atmosphere. The dynamics of the ocean circulation play a crucial role in natural climatic variability and, given appropriate initial values of the relevant oceanic variables, recent scientific advances have enabled predictions of shorter-period climate variations, such as the El Niño/Southern Oscillation phenomenon, that result from interactions of the oceans with the global atmosphere.

The Global Ocean and Ice research theme focuses on the dynamics of the slower components of the physical climate system, namely the ocean circulation and the mass balance of polar ice sheets. These components respond to disturbances with much greater inertia – longer "memories" – than the atmosphere, and therefore damp out fast changes (e. g. the seasonal cycle) and govern the pace of longer period climate variations. Because of the large mass and heat capacity of the ocean, the relatively slow oceanic circulation is responsible for approximately half the global equator-to-pole meridional heat transport. Ice sheets are expected to change on even longer time-scales, centuries to millennia. Nonetheless, recent discoveries point to the possibility of significant changes on much shorter periods.

Both the ocean circulation and the mass balance of large ice bodies are driven by conditions at their boundaries. The former strongly interacts with the atmosphere through exchanges of momentum, energy (heat), water, and other chemical substances. The ice sheets currently also play a dynamic role in the climate system; they create special atmospheric conditions locally (e. g. katabatic winds in Antarctica) and discharge large icebergs that influence the fresh water balance of the ocean. Polar ice sheets and other ice bodies constitute by far the largest fresh water reservoir on the planet. Even fractional melting of these ice sheets could cause very substantial rise in global sea level in the future, as has occurred in the past.

Because of strong ocean-atmosphere-ice interactions, it is not strictly legitimate to consider the dynamics of either component independently from the other on climatic time scales. Nevertheless, much remains to be learned by studying the responses of oceans and ice sheets to (observed or computed) surface forcing by the atmosphere. Such is the research paradigm followed in this chapter. The dynamics of the coupled ocean-atmosphere-land-ice system are considered in chapter 7 on Earth System Observations and Modeling, while the detailed studies of the "fast" atmospheric and hydrologic processes that occur in the atmosphere, in the atmospheric boundary layer and at the land surface are discussed in chapter 4 on Global Water and Energy Cycle research.

5.1 MAIN SCIENCE QUESTIONS

- ***How is the global ocean circulation varying on climatic time scales?***

The circulations of the Earth's oceans and the global atmosphere provide the mechanism by which the excess energy received from the Sun in the tropics is redistributed to the whole planet. Heat transport by the oceans amounts to about half the cycling of heat from equator to pole. The oceanic circulation also controls the supply of nutrients that feeds marine productivity and modulates the global biogeochemical cycles (notably, the carbon cycle). Any significant change in the oceanic circulation that results in variations of ocean surface temperature patterns has an immediate impact on atmospheric winds, weather and climate. The best known among these variations are the transient changes associated with El Niño/Southern Oscillation (ENSO) phenomena; the existence of other modes of variability is surmised, but establishing the statistical robustness of such preferred modes, characterizing the mechanism that may cause them, let alone predicting their future evolution and their impact on climate, are major scientific challenges. A record of variations in the global ocean circulation is an essential information basis to address this problem.

- ***Will climate variations induce major changes in the deep ocean?***

The deep ocean circulation and the rate of formation of "deep water" that sinks to intermediate or bottom depths have profound implications on the long-term storage of excess heat and chemicals in the ocean's depths; the recycling of nutrients; marine productivity and the carbon cycle; and the long-distance transport of heat from one ocean basin to the other. There is theoretical (modeling) evidence that the overturning circulation of the Atlantic ocean could be very sensitive to freshening of surface waters; compelling paleoclimatic evidence exists that Atlantic deep water formation was drastically reduced during certain periods in the past, notably during the recovery from the last glacial episode. A potential transition from the current overturning circulation to a regime where deep water formation is blocked would have a major climatic impact on the North Atlantic region. Quantitative knowledge of ocean circulation processes and understanding changes in the ocean fresh water budget will be needed to provide a reliable answer to this question.

- ***Are polar ice sheets losing mass as a result of climate change?***

Polar ice sheets, principally over Greenland and the Antarctic continent, constitute the largest reservoir of fresh water on the planet, corresponding to about 2% of the mass of the global oceans. Change in the mass balance of these ice sheets would result in major changes in the global volume of ocean waters and global sea-level. Airborne surveys of the Greenland ice sheet show little elevation change over most of the interior of the ice sheet above 2000 meters in height, but some areas of significant elevation change – predominantly thinning – around the coast. Assessing the rate of change of the much larger Antarctic ice sheet remains a major challenge, which can only be met through combined space-based topographic surveys and supporting *in situ* measurements or model estimates of variations in snow accumulation.

- ***Will changes in polar ice sheets cause a major change in global sea level?***

While an evaluation of the mass balance of the ice sheets is important for determining their current behavior and contribution to sea level change, any understanding of their likely future behavior requires an understanding of their dynamics and sensitivity to external forcing. The traditional concept of continental ice sheets as a sluggish component of the Earth system, changing literally with "glacial" slowness, is being superseded by the realization that parts of the ice mass are actually capable of changing substantially over periods of a few years or decades. The dramatic calving of vast tabular icebergs from relatively unstable ice shelves surrounding the Antarctic Peninsula is a portent of such changes. The first high-resolution radar survey of the Antarctic ice sheet discovered massive ice-streams, huge rivers of ice reaching far inland and leading to the ice sheet margin. Assessing the potential for relatively fast ice flows that could discharge vast volumes of ice in a matter of decades instead of centuries is a portentous problem, considering the global consequences of a possible acceleration of sea-level rise.

5.2 SCOPE AND NATURE OF THE PROBLEM

Climate research actually addresses two distinct scientific problems. The first problem is that of understanding and predicting climatic variations that form part of the natural variability of the Earth system, on time scales from a few months or years to decades and centuries. The second problem is determining the extent to which known or anticipated changes in climate forcing factors (e. g. the composition of the atmosphere) can influence global climate. There is no evidence that the intrinsic (unforced) variability of the atmospheric circulation can, by itself, induce persistent and predictable climate changes: statistically significant climate variations must therefore be governed by the slower components of the climate system, or driven by changes in external forcing such as transient increase in stratospheric aerosol loading caused by a volcanic eruptions. Understanding climatic variations requires knowledge of the dynamics of the slow components of climate, principally ocean and ice. The effects of anomalous hydrologic conditions over continents also can persist over periods of weeks or months, but barely qualify as "slow" in this context (see Chapter 4). The effects of changes in terrestrial ecosystems can last for longer time periods, but the nature and amplitude of resulting climate impacts are still unclear (see Chapter 2).

Any conceivable scientific strategy to explore the full range of climatic variability must rely, at some stage, on artificial records generated by numerical models of the interactive atmosphere, ocean, ice and land system; accumulating observational records over decades or centuries is not a realistic option for immediate results and paleoclimatic/historical information is generally insufficient to reach definitive conclusions regarding the operative mechanisms. While satellite observations afford us a global view, model simulations give us access to the time dimension. The problem is that of constructing, for instance, sufficiently realistic models of the global ocean circulation on the basis of a relatively brief observational record or "snapshot" of the evolution of the natural system. The development of fully coupled Earth system models that could be used with confidence to investigate the variability of the climate is considered in Chapter 7.

5.2.1 Global Ocean Circulation Variability

Sea surface temperature (SST) is a principal governing parameter of air-sea interaction and the first global indicator of change in ocean circulation and climate. SST variability is the result of radiative transfer (shortwave and longwave heat fluxes), air-sea interaction (sensible and latent heat heat fluxes), mixing of surface waters (entrainment), and horizontal movement of ocean waters (advection). SST is known to vary strongly on interannual time scales in the tropical Pacific Ocean (e.g. El Niño) and to vary coherently on decade-centennial time scales in Atlantic and Pacific Oceans. In the Atlantic cold and warm epochs coincide with variations of the North Atlantic Oscillation (NAO). In the Pacific a broad meridional SST variation has been identified with longer time scales than El Niño, referred to as the Pacific Decadal Oscillation (PDO).

The ***extent of sea-ice*** over the polar oceans is also a sensitive indicator of climate change, as the annual cycling of the ice cover is determined by a finely tuned balance between radiant heat loss, heat exchanges with the ocean and atmosphere, and the absorption of solar radiation during summer (the latter being strongly dependent upon the rapidly changing optical properties of dry or melting snow and ice). Recent observational evidence indicates not only a significant decreasing trend in the extent of sea ice over the Arctic ocean, but also a decrease in mean sea-ice thickness. The permanent disappearance of summer sea ice in the Arctic, a distinct possibility under plausible climate warming scenarios, would have a major amplifying effect on global warming at high northern latitudes. Both sea surface temperature and the extent of sea ice are routinely monitored by operational observing systems.

Knowledge acquired in the past about ***ocean currents and sea level*** was derived from *in situ* oceanographic and tide gauge observations available from a limited set of coastal stations or oceanographic cruises. Only space-based observation can provide the global coverage, spatial resolution, and sampling frequency necessary to capture the full range of variability in the surface circulation of the global ocean. Space-based measurements of the height of the ocean surface provide information on the combined effects of expansion or contraction of the water column due to changes in water properties and changes in mass above the reference surface (geoid) such as those associated with the wind driven circulation. Altimetry reveals changes in the sub-surface temperature structure and heat content of the ocean, as was observed in the tropical Pacific before the inception of the 1997-98 El Niño event, thus allowing reliable prediction of this climate event.

Accurate knowledge of the Earth's ***gravity field*** and ***the Earth's center of mass*** is also necessary to translate the raw satellite altimetry data into useful dynamic information (height above the reference surface for gravitational potential or "geoid"). Gravity field data expected from the forthcoming GRACE mission will raise our knowledge of the geoid to a new level of accuracy, comparable to the precision of altimetric measurements. In the future, it is anticipated that further technical advances will enable detecting transient changes in the Earth gravity field, effectively measuring the gravitational signature of changes in mass distribution at the surface of the planet. Such gravity measurements will enable mapping the time-dependent distribution of ocean mass (in effect ocean bottom pressure) and reveal more about ocean mass transport.

Pacific Ocean and the Southern Oscillation

The El Niño-Southern Oscillation (ENSO) phenomenon is governed by the basin-wide response of the tropical ocean circulation to anomalous surface winds, and the (local) response of the tropical atmosphere to circulation-induced changes in sea-surface temperature. While the active core of the phenomenon is localized in the tropical Pacific ocean, ENSO is a coherent global oscillation which is felt worldwide, and more strongly so in Australia, Southeast Asia, and the Americas. The basic ENSO mechanism is well enough known that predictions can be made several seasons in advance, using *in situ* observations and space-based measurements (especially ocean surface topography and winds). Past climatological record shows considerable decadal to centennial variations in the recurrence frequency and strength of ENSO phenomena. For instance, the two largest known El Niño events of the century have occurred during the last 15 years. It is not known whether this was a random occurrence within the normal range of natural variability, the result of a multi-decadal transient anomaly in the circulation of the Pacific ocean (an hypothetical "Pacific Decadal Oscillation"), or a consequence of global climate warming. Investigating the long-term variability of the ENSO phenomenon will require much deeper understanding of dynamics of basin-wide oceanic circulation and the physics of air-sea interaction. Both present major scientific challenges.

5.2.2 Change in the Deep Ocean Circulation

The oceans constitute by far the largest heat reservoir in the Earth's climate system. Any excess energy in the net planetary radiation budget is absorbed principally by the oceans, thus causing a progressive warming of ocean waters. Depending upon the depth reached by this ocean warming, the effective thermal inertia may be smaller or larger, determining the time delay before temperature rises at the surface. Furthermore, the thermal expansion coefficient of ocean water, which determines the change in the total ocean volume for a given heat intake, depends upon temperature and depth; detailed knowledge of the total water column ocean circulation is essential for a reliable assessment of future sea-level rise and its variation globally. Finally, ocean water subduction entrains carbon into the deep ocean, while oceanic upwelling brings nutrient-rich deep waters near the surface. The geographical location and temperature of upwelling waters are controlling factors in the planetary carbon cycle and atmospheric carbon dioxide, marine ecosystems and, eventually, fisheries.

Mechanical stress produced by wind is the principal driver of upper oceanic motion on all scales, from oceanic turbulence and upper ocean mixing to basin-scale currents. Because of the nonlinear interactions linking different scales, accurate simulation of the ocean circulation requires detailed knowledge of ocean surface wind at relatively fine space and time scales. The rotational component of the wind stress induces vertical upwelling motions that play a major role in thermal and chemical balance of the oceans. While wind stress is the principal driving force in the upper ocean, the deep ocean circulation is largely thermohaline (i.e. largely controlled by the temperature and salinity structure of the ocean). The formation of deep water from saline surface water exposed to cold air is the primary mechanism that drives the deep ocean circulation connecting all ocean basins. The circulation time scales of deep waters range from decades to millennia, thus making the deep ocean circulation the principal physical agent in long-term climatic variations and long-term trends.

Deep water formation is expected to be sensitive to freshening of surface waters, brought about either by the import and subsequent melting of sea or land ice, or by climate-induced changes in the fresh water balance of the ocean at tropical and mid-latitudes. Since atmospheric temperature at high latitude always falls below the freezing temperature of sea water, the fate of superficial waters and their ability to sink into the deep ocean depends upon their pre-existing salinity (salinity and temperature are the two parameters that determine water density). Thus, the principal observational requirements for investigating the potential for a transition in ocean circulation regime are (exploratory) measurements of ***sea surface salinity*** as well as observations of ***sea-ice*** formation, transport and melting processes**.**

Air-Sea Interactions

The physical characteristics of deep ocean waters are largely governed by air-sea interaction at high latitude, while many of their chemical characteristics are determined by the downward flux of biogenic material. Determining the heat, momentum, and fresh water fluxes at the ocean-atmosphere interface is a major challenge of climate research, basically because of the wide disparity in the masses and heat capacities of the two media. The atmosphere may respond to surface flux anomalies on the order of 10-100 Watt/m^2 over periods of days. The oceanic circulation responds, over periods of years, to time-averaged net energy fluxes on the order of a few Watt/m^2 or net water fluxes (precipitation minus evaporation) one or two orders of magnitude smaller than instantaneous rainfall or evaporation. Air-sea fluxes are traditionally computed by means of bulk aerodynamic formulas involving surface wind and near-surface vertical gradients of the relevant properties. Such simple aerodynamic formulas cannot be legitimately extrapolated to data-sparse areas, using global remote sensing data sets that do not resolve near-surface gradients, or information from models that do not reproduce relevant boundary layer processes. Much progress will be needed in both global observation of the marine atmosphere and model computations of surface fluxes to advance in this domain.

North Atlantic Climate Change

The analysis of atmospheric and oceanic records has revealed a coherent pattern of decadal variability in mid-latitude winds in the northern hemisphere, together with variations in sea-surface temperature (SST) and sea-level pressure over the North Atlantic, including occasional incursions of sea-ice and salinity anomalies from the Arctic. This "Arctic Oscillation" of the global atmosphere, also referred to as the "North Atlantic Oscillation" over the region where the most active air-sea interaction occurs, influences weather in North America and Europe and may be related to changes in precipitation over the African continent and Brazil through tropical SST variations. No definitive indication exists at present of the nature of underlying mechanism(s). On longer time-scales, coupled atmosphere-ocean model simulations suggest a significant weakening of the meridional overturning circulation and heat transport in the Atlantic ocean basin, that may change the current mild climatic conditions existing at high northern latitudes over the Atlantic seaboard and Europe. The immense economic disruptions that would result from such climate change make the long-term stability of the Atlantic ocean circulation a highly charged geophysical research issue.

Antarctic Circumpolar Wave

Sea-ice dynamics is usually perceived as a short-period response to wind, radiation or oceanic forcing fluctuations, but longer period variations do exist. The recently discovered Antarctic Circumpolar Wave is such an oscillation in sea ice-extent and local concentration, accompanied by related variations in surface wind and sea-surface temperature, that run a full circuit around the Antarctic continent in about 8 years. No atmosphere-ocean-sea ice coupling mechanism has yet been identified to conclusively explain this phenomenon. Similar propagation of disturbances in the edge of the ice pack has also been observed in various regions of the Arctic.

5.2.3 Mass Balance of Polar Ice Sheets

General sea-level rise results from the thermal expansion of ocean volume and/or addition of meltwater from mountain glaciers and polar ice sheets. Sea level change at a particular site may also reflect changes in ocean circulation (a 50cm rise in sea level at some Pacific island sites may result from ENSO events), as well as geological processes such as continental uplift or subsidence. Crust rebound rates from lifting the ice load accumulated during the glacial period are as large as 1m per century at some locations around the coast of Scandinavia. The scope for serious environmental impacts is obviously very large, since a large fraction of the world population resides in coastal areas. Even a 10cm rise, as anticipated in the next 30-50 years, will threaten coastal wetlands, increase the exposure to storm surges and wave damage, induce increased coastal erosion and allow substantial encroachment of salt water in near-shore aquifers. Numerous cities built near the sea-shore in region subject to geological subsidence are now very sensitive to further sea-level rise.

The well-documented retreat of alpine glaciers since the climax of the Little Ice Age is the most dramatic early indicator of a global climate warming trend. Total melting of remaining mountain glaciers would only raise the global mean sea-level by an additional 50cm. On the other hand, mountain glaciers are retreating fast and their contribution to sea-level rise could be larger than the contribution from polar ice sheets through the next century.

The melting of the ice stored in the Greenland and Antarctic ice sheets would be sufficient to raise the level of the world ocean by 75m. We know that ice sheets alternatively advanced and retreated during several million years, causing changes in global mean sea level in excess of 100m. We also know that any net change currently occurring in ice sheet mass balance must be quite small, consistent with a rate of sea-level rise on the order of a few cm per century. Yet, during the period of recovery from the last glacial maximum, sea level rose at a rate exceeding 1m per century. Very little is known, quantitatively, about the dynamics of the polar ice sheets, the input and output terms of their mass balance and the potential for rapid evolution, given the range of potential changes in polar climates.

The goal is to quantify (or confirm the absence of) relatively fast changes in the mass balance of polar ice sheets and this implies measuring the total volume of the ice sheets and their flux. NASA has made significant progress in developing instrumentation to support this objective and satellite observing techniques including precision lidar altimetry and radar imaging have recently become available. These techniques will be used to survey both major ice sheets and will acquire information comparable to that already derived by NASA from aircraft observations over the Greenland ice sheet.

5.2.4 Ice Sheet Dynamics and Sea-Level Rise

In the traditional view, the rate at which ice sheets could conceivably deliver water to the ocean is inversely related to their size. This reassuring view may turn out to be short-sighted, as it ignores the relatively fragile equilibrium of parts of the polar ice sheets, such the West Antarctic marine ice sheet, and the existence of 1000km long ice streams that reach far inland and could drain ice much faster than the traditional picture would imply. Currently, the combined uncertainty in the mass balances of the Greenland and Antarctic ice sheets is larger than the uncertainty about sea-level rise from all other causes. The recent break-up of large ice shelves fringing the Antarctic Peninsula have focused attention on the possibility of a collapse of additional ice reservoirs further south within a relatively short time period. Changes in floating ice shelves will not affect sea level directly, but their break-up would allow the ice sheet upstream to flow more freely toward the ocean. The observational requirement is mapping the ***velocity fields*** of the two great ice sheets of Greenland and Antarctica in order to identify their dynamic regions and estimate the mass fluxes of major ice streams. The relevant (synthetic-aperture radar) data might be obtained commercially, or from dedicated national or international scientific measurement missions. Regional airborne campaigns that are able to shed light on the internal and basal properties of major ice streams will complement such spaceborne campaigns and will support the development of models.

EXPECTED SCIENTIFIC ACHIEVEMENTS

Question 1: How is the global ocean circulation varying on climatic time scales?

Expected new knowledge in the next 5 years

- High-resolution structure of the global ocean surface wind field;
- Global upper-ocean circulation data assimilation and prediction, including ENSO forecasts with ocean-atmosphere coupled models;
- Improved coastal ocean predictions through assimilation of global and local data;
- Global diagnostics of transient sea-ice cover and flux anomalies.

Expected new knowledge in the next 10 years

- Estimation of the state of the world ocean circulation down to eddy-scale motions, based on model assimilation of global ocean data;
- Linkage between the global ocean circulation and the frequency and intensity of ENSO events;
- Linkages between sea ice anomalies and high latitude atmosphere and ocean anomalies.

Question 2: Will climate variations induce major changes in the deep ocean?

Expected new knowledge in the next 5 years

- Global diagnostics of transient sea-ice cover anomalies;
- Experimental global diagnostics of sea-ice thickness;

Expected new knowledge in the next 10 years

- Relationships between global sea-surface salinity, riverine inputs, sea ice anomalies and deep water formation rate;
- Linkage between the Atlantic Ocean circulation and global atmospheric climate.

Question 3: Are polar ice sheets losing mass as a result of climate change?

Expected new knowledge in the next 5 years

- Baseline high-precision data base of Greenland and Antarctica elevations;
- Estimation of the current mass balance of the Greenland ice sheet;
- Current trend in global mean sea-level based on a ten-year record of satellite altimetry data.

Expected new knowledge in the next 10 years

- Development of models relating high-latitude climate to mass loss/gain over both polar ice sheets;
- Baseline determination of the total mass of the Antarctic Ice Sheet;
- Estimation of the mass balance of key Antarctic catchments.

Question 4: Will changes in polar ice sheets cause a major change in global sea level?

Expected new knowledge in the next 5 years

- High resolution maps of Greenland and Antarctic ice streams and estimates of flux for major catchments;
- Initial development of models of ice stream dynamic behavior

Expected new knowledge in the next 10 years

- Description of ice stream dynamics and sensitivities to external forcing;
- Data analysis and models relating ice sheet accumulation and mass loss to climate

5.3 PROGRAM ELEMENTS

Common to the four scientific questions formulated above is the need for an effective inter-agency as well as international research strategy, such as laid out by the World Climate Research Program: no single nation, let alone science-funding agency, has the means to investigate climate problems of such global extent and multi-disciplinary scope. The NASA effort currently focuses on global measurements of the ocean circulation and the mass of polar ice sheets, and seeks fundamental understanding of the dynamics of these slow components of the climate system. Currently, a special effort is devoted to understanding and predicting ENSO phenomena (and other short-term climate variations). As global ocean modeling capabilities and computing resources develop, the research effort is expected to shift toward investigation of ocean and ice dynamics on longer time-scales.

Characterizing and understanding the current variations in global ocean circulation calls for new global space-based observations of oceanic variables, as well as development of modeling tools to assimilate such satellite data together a wide range of contemporaneous *in situ* oceanographic measurements. The principal thrust NASA research in this domain will be understanding the dynamics of the ocean circulation and developing the capability to predict the response of the ocean circulation and sea ice to changes in surface forcing, on the basis of relatively short global oceanic data sets spanning only 10-20 years. As global oceanography is still in a development stage, scientific progress is critically dependent upon new global observations of the ocean circulation, sea-ice, and surface fluxes of momentum, heat, and fresh water (see Section 5.3.1).

Understanding the response of the deep ocean circulation to climate change is an even more difficult problem, involving in a crucial way the coupling with the atmospheric circulation, energy transformations, and water budget, as well as internal ocean processes. The principal thrust of the NASA program will be acquiring global observations of ocean and sea-ice properties (sea surface temperature, salinity, and winds; sea-ice deformation and thickness) and enable inferring the heat and fresh water budgets of the ocean (see Section 5.3.1).

Assessing current changes in the mass balance of polar ice-sheets calls for advances in quantitative characterization of year-to-year changes in ice sheet topography and estimates of annual snow accumulation and mass losses, based on supporting snow and ice core data, ice velocity maps, iceberg discharge data, model assessments of precipitation, etc. It is particularly important to establish the inter-annual variability in snow accumulation and ice losses in order to understand the significance of mass balance estimates. In the course of the past ten years, NASA has participated with NSF and other science funding agencies abroad in the study of the Greenland ice sheet, and has spearheaded a systematic Greenland *in situ* and airborne survey program (NASA, 1999) to determine current trends in the Greenland ice-sheet mass balance. The focus of the NASA contribution will be the extension of these surveys to the Antarctic ice sheet, using satellite-based precision altimetry and gravity measurements (see Section 5.3.2).) and continued efforts to establish effective satellite-based methods for mapping snow accumulation and ice loss.

Understanding the dynamics of ice sheets is important in order to evaluate the susceptibility of the ice sheets to future changes in mass balance. In particular, it is important to understand the extent to which ice streams, which transport most of the ice mass into the oceans, are sensitive to external forcing. There is clear evidence for past changes in the dynamics of ice streams and for current changes in the positions of some grounding lines, where ice streams begin to float. It is likely that some of these changes may reflect internal dynamics, but it is not clear whether this behavior is sensitive to more extreme changes brought about by external forcing. In order to understand the likely level of stability of the ice sheets, it is necessary to support radar mapping of surface ice velocities to reveal the area extent of the ice streams (Section 3.3.4) and to understand the internal and basal dynamics of ice streams by radar sounding and modeling. In understanding the stability of the major ice sheets, it is also important to establish the extent to which snow accumulation and ice loss is sensitive to changes in climate. This will require continued efforts to model interactions between snow accumulation, ice melting and climate at high latitudes.

5.3.1 GLOBAL OCEAN CIRCULATION AND SEA-ICE

The first global survey of the world oceans, completed by the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean Global Atmosphere (TOGA) programs of the World Climate Research Program, provided a description of the state of the global ocean circulation in the 1990's. The scientific community is now poised to effectively begin experimental time-dependent predictions of the global ocean circulation and its interaction with the atmosphere and cryosphere, in order to:

- Understand and predict how the oceanic circulation may affect sea surface temperature on time scales from days to years.
- Understand and predict how variations in atmospheric and oceanic circulation determine interannual and decadal fluctuations in the extent of sea–ice, as observed in the historical record.
- Assess the impact of changes in oceanic circulation on marine living resources, and
- Estimate how the oceanic circulation may influence the global carbon cycle and sea level.

This program requires time-series of global ocean/sea-ice data covering periods comparable to the characteristic time-scales of oceanic gyres (several decades). Estimating the full-depth global circulation of the ocean requires the synergistic application of multiple techniques: global observation of ocean surface parameters from space; *in situ* observation of the ocean density structure and transport (current velocity field and tracers); assimilation of ocean data from a variety of sources using ocean circulation models; and long-term simulation runs with high-resolution ocean circulation models (computing technology is the limiting factor). NASA supports this global ocean circulation research strategy and aims to contribute, together with operational environmental agencies and other partner agencies, to the realization of an ocean observing system combining *in situ* measurements with space-based observation, data processing and analysis.

5.3.1.1 Systematic Global Ocean Measurements

Consistent with the research strategy outlined above, the highest scientific priority in the discipline is systematic global measurement of five critical ocean surface variables that can be used, in conjunction with *in situ* oceanographic observations, to reconstruct the global ocean circulation: sea surface topography or dynamic height, vector winds, sea surface temperature, and sea ice concentration and dynamics. Measurement of these variables from space has already been demonstrated with the required accuracy and coverage. Satellite remote sensing is the only means to acquire almost instantaneous worldwide observations and thereby provides the appropriate diagnostic tool for understanding the time-dependent circulation.

Ocean Surface Topography

Ocean surface altimetry data provided by the NASA/CNES TOPEX-Poseidon mission (1992-present), the European ERS satellite series (1991 to present), and US Navy GEOSAT-1 (1985-90) ushered a new era of global dynamic oceanography, based on successive synoptic mappings of ocean surface height and the geostrophic ocean circulation. NASA plans are based on the prospect that altimetric measurements of sea level topography will eventually evolve into a component of an operational ocean observing system. The implementation of this measurement from operational environmental satellites in sun-synchronous polar orbit faces two unresolved technical problems:

- Correcting the effect of solar tides (aliased in sun-synchronous measurements) to the required accuracy of a few centimeters by means of a suitably advanced global tidal model.

- Providing the required space-time sampling of the most active ocean circulation features, as provided by the optimal TOPEX orbit

Pending the resolution of these questions, NASA plans to expand its cooperation with France and US agencies to continue small satellite missions dedicated to ocean altimetry. The TOPEX-Poseidon altimetry satellite continues to provide precision sea level data of 3-5 cm (RMS) accuracy, that are incorporated in the NOAA and NASA ENSO prediction systems (NASA Seasonal-to-Interannual Prediction Project). The follow-on program, beginning with the Jason-1 mission (to be launched in May 2000), is aiming to improve upon this accuracy and reduce the uncertainty to a 2cm (RMS) level. A principal objective of this and follow-on missions is to foster operational uses for a variety of applications, from ocean circulation prediction (coastal current, ENSO forecasts, etc.) to geophysics.

It is presently envisioned that the successor Jason-2 mission could be a cooperative effort of the US and French space agencies, with the participation of operational agency partners. Jason-2 would prolong for a nominal five year period the time series of high-precision altimetry data initiated with TOPEX-Poseidon and Jason-1 (Box 7). Although significant further work will be needed to develop a real-time acquisition system for a high-quality ocean altimetry data, and assimilate effectively these data in ocean models, active steps are being taken, notably under the Global Ocean Data Assimilation Experiment (GODAE), to ensure that operational applications are practical and widely accepted. The real-time availability of precise sea-level measurements from space is the innovation that makes operational oceanography viable, and justifies a national initiative to create a global ocean observing program combining the resources of research and operational agencies (see Section 3.3.1.3).

Box 7
Ocean Surface Topography Mission

Based on the heritage of the very successful TOPEX/Poseidon radar altimetry mission, the Jason-1mission is a joint project of NASA and the French space agency CNES. Jason-1 will carry a two-frequency radar altimeter derived from the CNES-provided instrument on TOPEX/Poseidon, as well as a microwave radiometer for simultaneous measurement of total water vapor in the air column. The latter is necessary in order to correct significant spurious propagation delays introduced by natural variability in atmospheric water content.

Jason-1 and subsequent repeat missions will be placed on the TOPEX/Poseidon orbit (1336 km altitude, 66° inclination circular orbit) that provides optimal time and space sampling of the active dynamical components of the oceanic circulation and ocean tides. The objective is to enhance the altitude determination accuracy and reduce residual errors to 2cm RMS in calm to moderate sea state conditions.

Ocean Surface Wind

The wind vector field over the surface of the ocean constitutes an essential boundary condition to drive ocean circulation simulations and predictions. Both active (scatterometer) and passive (polarimeter) microwave measurement techniques can be applied to determine vector wind. The wind vector accuracy (of order 1 m/sec over the full range of wind speeds) required in principle for global ocean dynamics prediction remains to be demonstrated by either technique, however, although scatterometer wind data are close to this goal. Building on the heritage of the NASA Scatterometer (NSCAT) sensor flown on the Japanese ADEOS mission in 1996-1997, the agency has developed a successor instrument (Seawinds) which will fly on two overlapping missions: QuikScat (launched in June 1999) and Japan's ADEOS-2 to be launched in late 2000. At the same time, the Navy is preparing a experimental satellite mission (Coriolis) to test the passive microwave technique for vector wind finding applications (see Box 8). Further improvement of the NASA wind scatterometer is contemplated with a proposed AlphaScat sensor that could fly on Japan's follow-on Global Change Observation Mission (GCOM B-1) in 2005.

The Seawinds missions will be followed in 2003-2004 by the operational deployment of the ASCAT wind scatterometer sensor (developed by the European Space Agency) on the European METOP environmental satellite series. Further downstream, the NPOESS program is planning to deliver daily quasi-global vector wind data based on passive microwave polarimetry (Conical-scanning Microwave Imager/Sounder). NASA may continue its cooperation with Japan to maintain a capability for precision global wind observation based on active microwave measurements on Japan's GCOM environmental research satellite series.

Box 8
Ocean Surface Wind

NASA has launched the Seawinds wind-finding microwave scatterometer on its QuikScat mission (June 1999) and provided a model of the same instrument for flight on Japan's ADEOS-2 mission in late 2000. The second generation Seawinds instrument is expected to provide unequalled precision (on the order of 1-2 m/sec), horizontal resolution (25 km) and a broad swath width allowing daily coverage of the world oceans with minimal gaps.

Pending the results from the Seawinds (active) and Coriolis (passive microwave) wind remote sensing demonstration projects, NASA is studying the opportunity of deploying an advanced technology version (AlphaScat) of its current wind-finding scatterometer on Japan's Global Change Observation Mission (GCOM) satellite series and/or future NPOESS operational satellites.

For the future, an alternative method based on surface scattering of GPS signals shows promise as a means to estimate surface winds globally with unprecedented spatial and temporal resolution. Research on GPS reflection and scattering phenomenology is a priority research avenue for NASA's physical oceanography program.

Sea-Surface Temperature

Sea surface temperature (SST) is the only property of the open ocean that directly affects the general circulation of the atmosphere. SST is also very sensitive to changes in ocean circulation, as demonstrated time and again by wind-driven ENSO events. For these reasons, and also because sea surface temperature has been measured quite accurately by ocean-going vessels over a period of several centuries, long-term SST records are a most valuable source of information on climate variability and trends. Quasi-synoptic global SST fields are derived operationally, for a variety of applications, by merging global radiance measurements from operational satellites (NOAA/AVHRR) and *in situ* observations by ships of opportunity and a relatively thin network of moored and drifting buoys. The climate science community currently depends on these operational SST products for climate and physical oceanography research, even though the accuracy achieved in this operational context (0.5-0.7°C) is marginal for some scientific investigations (in the tropics, a 0.2-0.3°C temperature anomaly may be enough to change evaporation materially).

Improving the precision of SST remote sensing is essential to achieve adequate and essentially uniform accuracy worldwide, even in regions where *in situ* measurements are scarce. Significant progress is expected with the MODIS radiometer on EOS Terra and Aqua, on account of the sophisticated on-board calibration and accurate corrections for atmospheric water vapor and aerosol. Equally significant improvement in SST retrieval is also expected with the Atmospheric Infrared Sounder (AIRS) on EOS Aqua on account of superlative ability to correct for atmospheric absorption. Atmospheric corrections are considerably smaller for microwave radiometry: the significant advance demonstrated with TRMM Microwave Imager (TMI) measurements, and further technical refinements expected with the Advanced Microwave Scanning Radiometer (AMSR) on the EOS Aqua mission and the Advanced Technology Microwave Sounder (ATMS) on the NPP mission (see Box 3) will allow combined retrievals of ocean surface wind speed (sea state) and temperature that can match and possibly improve upon the accuracy of current global SST retrievals. NASA will continue to experiment with both infrared and microwave radiometry techniques for precision remote sensing of SST in the coming decade.

Sea-Ice Extent/Concentration

Sea ice modulates planetary heat transport by insulating the ocean from the cold polar atmosphere, and also by modulating the thermohaline circulation of the world ocean through the process of brine rejection. Moreover, the high albedo of snow-covered ice further insulates the polar oceans from solar radiation and introduces yet another positive feedback in the climate system. Systematic global observation of sea-ice extent and concentration, inferred from passive imaging microwave radiometry data, has produced an invaluable 20-year record of global sea-ice concentration. There is strong scientific justification for continuing this type of observation in the future, notably for early detection of impacts of the global greenhouse effect on the climate of the polar regions. Time series of sea-ice concentration data are also critical for identifying interannual and decadal fluctuations that could point to the existence of significant changes in oceanic and atmospheric circulations at high latitude.

NASA will rely primarily on the Advanced Microwave Scanning Radiometer (AMSR) provided by Japan on the EOS Aqua mission and operational satellite sensors (DMSP/SSM/I; NPOESS/CMIS) to ensure the continuity of the global sea-ice concentration record. The EOS/MODIS sensor also has the potential for advances in remote sensing of sea-ice conditions, by virtue of its high spectral resolution and provisions for deriving effective high-latitude cloud masks. Dual polarization synthetic aperture radar (SAR) observations provide the potential to make a significant improvement in our capability to map sea ice type and particularly to resolve areas of thin ice where most of the heat flux takes place. Active microwave scatterometer observations, provided by ADEOS, QuikScat, and the series of European METOP operational meteorological satellites, can also provide sea-ice concentration information, albeit at slightly reduced spatial resolution. The agency will continue to support global climatological studies based on a range of passive and active microwave measurements (imaging radiometer and scatterometer) and basin-wide studies using higher resolution sensors (including SAR).

Sea-Ice Dynamics

Sea-ice constitutes a mobile layer over the surface of the polar oceans, driven by atmospheric and ocean forcing. The motion of this layer forms a large-scale pattern of circulation that evolves over periods of years. Changes in the large-scale circulation of the ice pack may provide insight in the response of the high latitude environment to, and in turn influence on, ocean and atmosphere circulation at lower latitudes. Wide-swath active microwave instruments (Seawinds) and passive radiometers (AMSR) have a demonstrated a robust capability for mapping sea-ice drift in the polar regions: NASA will continue to encourage investigations based on the analysis of these data to link high-latitude ocean and atmospheric dynamics to global climate.

The motion of sea ice creates patterns of ice convergence and divergence that play a critical role in determining energy and momentum fluxes between the ocean and atmosphere at high latitudes. Furthermore, the production of new ice in areas of ice opening regulates the formation of deep water masses. High-resolution synthetic aperture radar (SAR) data constitute an ideal tool for basin-scale investigations of sea-ice motions, growth and deformation processes. The RADARSAT "Arctic Snapshot" program has provided SAR coverage of the majority of the Arctic every few days since 1996. These data are being ingested into the RADARSAT Geophysical Processor System and are generating large-scale sea-ice motion and deformation maps for the north polar region. Derived sea-ice products will be made available through the Alaska SAR facility and NASA will encourage the evaluation and broad application of these products by the polar community. SAR data will continue to assist in characterizing the detailed dynamics of Arctic sea ice and have the potential to reveal the dynamics of sea ice cover in the Southern Ocean.

5.3.1.2 Experimental Ocean Circulation Measurements

Precision Gravity Field or Geoid

Knowing the precise shape of the geopotential reference surface or geoid is essential in order to translate ocean surface altimetry data into absolute dynamic height information. The NASA Earth gravity mapping program (see section 5.3.2.1) will continue to use precision GPS receivers on geophysical research missions of opportunity led by international partner agencies to improve the determination of the earth gravity field at wavelengths of 1000 km or longer.

The experimental Gravity Recovery and Climate Experiment (GRACE) Earth System Science Pathfinder mission, currently being prepared in partnership with Germany, is expected to deliver more precise gravity field information (accuracy on the order of 1cm over scales of 300 km or longer). GRACE is also intended to measure, over a period of five years, minute variations in the Earth gravity field associated with transient changes in the distribution of fluid masses (see section 5.3.2.2). NASA is poised to exploit the extreme accuracy of present and future space-based gravity measurements to detect changes of the time-dependent distribution of ocean waters (equivalent to a global measurement of ocean bottom pressure).

Sea Surface Salinity

Ocean salinity, more than temperature, controls the dynamics of the deep ocean circulation and long-term climate. Sea surface salinity (SSS) determines the depth to which cold surface water may sink to form intermediate and deep ocean water masses. Despite the scientific significance of SSS, there is almost a total lack of systematic ocean salinity measurements worldwide, except for occasional oceanographic cruises and automated measurements on some merchant vessels. Thus, global remote sensing of SSS to a useful level of accuracy (better than 1 Practical Salinity Unit) would be a very significant achievement for global oceanography and global water cycle studies. Developing low-frequency microwave radiometry techniques for remote sensing of sea-surface salinity is a priority of the NASA physical oceanography program; aircraft test are being conducted to assess the feasibility of such measurement from space. The European Space Agency is currently studying a Soil Moisture and Ocean Salinity measurement mission (SMOS) that will test this measurement concept.

Alternative Approaches to Altimetry and Wind Measurement

The precision encoded transmission of the Global Positioning System has found many applications. Reflections of these signals off the sea surface are being examined for possible use as a source of wind speed and ocean surface topography information. The forward scattered GPS waveform depends on the roughness of the sea surface. The characteristics of the surface can be determined from the distribution of the reflected signal as a function of delay and Doppler. Wind speed is estimated using surface roughness models. Altimetric information can also be obtained although with significantly less accuracy than current radar altimeters. However, this measurement is still promising because of the significant increase in temporal/spatial coverage that might be obtained to complement precision altimetry missions. Scattering by the rough sea surface strongly attenuates the ocean-reflected GPS signal compared to that over a perfectly smooth ocean. For satellite reception, the large distance from the scattering surface accentuates this attenuation problem and significant increase in receiver antenna gain will be required and remains a technological challenge.

Sea Ice Thickness and Snow Cover

Sea-ice thickness and concentration are the primary variables for estimating sea-ice growth, melting, and mass transport by ocean currents (or equivalent fresh water transport), and for inferring energy and momentum fluxes across the ice-covered ocean surface. No current technique exists for the direct determination of sea-ice thickness from space. A new approach, using the RADARSAT Geophysical Processor System, is intended to estimate sea-ice thickness by monitoring ice divergence and convergence in Lagrangian cells moving across the Arctic and thence using an ice growth model to estimate ice thickness from ice age. The accuracy of such thickness estimates will depend critically on the reliability of the ice thickness growth model used in their derivation, as well as the accuracy of supporting meteorological information. The capability to acquire extensive measurements of sea-ice thickness represents the ultimate challenge of sea-ice remote sensing, as this quantity is so critical to the estimation of energy and momentum fluxes between the ocean and atmosphere.

Snow cover also plays an important role in determining the energy balance of sea-ice, as it adds substantial insulation from the atmosphere and modulates albedo. Yet, even the climatology of snow thickness distribution over sea ice is known only in the crudest terms. NASA will be interested in the development of experimental methods for estimating this parameter using space-borne sensors such AMSR. Ice surface temperature and albedo have also eluded routine observation to date, largely because of difficulties in separating cloud cover from snow and ice cover in visible and infra-red image data. New sensors such as MODIS may assist in addressing this problem.

Global Ocean Data Assimilation Experiment

The Global Ocean Data Assimilation Experiment (GODAE), currently in the planning stage, aims to provide a three-year demonstration of the usefulness of global ocean data assimilation products in the time-frame 2003-2007, utilizing real-time remote sensing and *in situ* data. If successful, GODAE will provide the proof of concept for operational ocean diagnostics and prediction on a global scale. This demonstration may include participation with other interested agencies, in the US and abroad, in the deployment of a basin-wide or global system of profiling floats, as part of the Array for Real-time Geostrophic Oceanography (ARGO) project. ARGO is an internationally sponsored project to deploy a global array of some 3000 ARGO profiling floats, that would complement global satellite observations and automatically acquire ocean temperature and salinity profile data. NASA will play a key role in developing the data assimilation component of GODAE, as needed to produce consistent analyses of the state of the oceanic circulation (see below).

5.3.1.3 Ocean and Polar Research Field Campaigns

Since ocean remote sensing is currently confined to its upper surface, *in situ* measurements are indispensable to characterize the vertical structure of the ocean and interpret the meaning of satellite data. This constraint will remain a reality over the coming decades and is the basis for strong interagency cooperation in the ocean research program. Over the last decade, NASA oceanographic process studies have been planned jointly with other federal agencies and embedded within the international World Climate Research Programme (WOCE and TOGA programs). Similarly, sea ice processes have been studied in partnership with other agencies, e. g. the NSF-led SHEBA ice camp project.

Future plans for ocean instrument deployments are being driven by the opportunity of GODAE. NASA is assisting in the design of the ARGO profiling float array and expects to be a primary scientific user of the data provided by that system. As a general rule, NASA will concentrate its resources on special-purpose ship- or aircraft-based field measurement campaigns focused on validation and testing of new remote sensing systems (e.g. remote sensing of surface salinity and sea ice properties). NASA is interested in the development of integrated in situ and space-based measurement systems and will support, to the extent possible, the development of the required technological capabilities.

NASA participated with NSF and other US agencies in a major, year-long field study of sea-ice and related processes (SHEBA ice camp project). This campaign provided a wealth of information on sea-ice growth, deformation and melting, sea-ice energy budget, and polar atmosphere and cloud properties. This information is currently being analyzed to determine the nature and importance of interactions between the ocean, ice and atmosphere and to establish and test methods for monitoring the polar oceans from space-borne sensors. The challenge will be to translate the results of these process studies to the scales of global circulation models. Future field campaigns are being envisaged by NASA, in collaboration with other agencies, to support *in situ* validation of satellite polar remote sensing products.

5.3.1.4 Global Ocean Circulation Modeling and Data Assimilation

Ocean model development in this program is closely linked to the analysis of global ocean data obtained from satellite and other observations. Synergistic use of models and data analysis is the principal approach for diagnosing the causes of ocean behavior or elucidating the physics of processes. NASA will maintain an active involvement in ocean model development and ocean data assimilation with the objective of providing a capability for estimating and predicting the state of the ocean circulation. This will be accomplished, in cooperation with NSF, by supporting the World Ocean Circulation Experiment (WOCE) analysis, interpretation and modeling activities. For the future, the principal focus for research and application will be the Global Ocean Data Assimilation Experiment (GODAE), currently in the planning stage. If successful, GODAE will provide the proof of concept for operational ocean diagnostics and prediction on a global scale. This work relies on a heritage of well-used community models and extensive engineering of the model efficiency. More general scientific and theoretical development of the model ocean circulation is supported as significant model deficiencies are occasionally demonstrated through data analysis. Treatment in global models of such subjects as the

Pacific-to-Indian Ocean flow through the Indonesian Archipelago, fluxes due to mesoscale eddies, and appropriate treatment of the weak deep circulation have motivated past NASA support. The potential of data assimilation will also be explored within the context of sea ice monitoring. NASA will continue scientific model development in the context of improving community models (see also Chapter 7: Earth System Observations and Modeling).

5.3.2 Ice Sheets and Glaciers

It is not known definitely whether the Antarctic and Greenland ice sheets are currently decreasing or increasing in mass. A high priority of the NASA research program on climate variability is to reduce the uncertainty in these measurements, and improve our ability to predict future ice-sheet behavior. The primary purpose of the ICEsat (Ice, Cloud and Land Elevation Satellite) mission, to be launched in July 2001, is to provide a baseline for estimating trends in the ice sheet mass balance by comparison with repeat measurements by later precision altimetry missions.

Many satellite data show promise for obtaining quantitative estimates of key ice-sheet parameters. Passive microwave sensors and scatterometers have offered insight into patterns of accumulation and ablation on the ice sheets while Landsat-7 and ASTER data will contribute to mapping of glaciers and their zones of melt and accumulation where higher spatial resolution is required. In recent years, SAR data has proved itself invaluable as a tool for exploring conditions across the great ice sheets. The twin European ERS missions and the Canadian RADARSAT Antarctic Mapping Project, in particular, have produced a wealth of synthetic-aperture radar (SAR) images of the Antarctic ice sheet.

The RADARSAT mission provided the first high-resolution radar map of the entire Antarctic continent, revealing information that promises to change the paradigm of Antarctic research. It is expected that a second Antarctic Mapping Mission, with an interferometric design, will allow the detection of significant changes in Antarctic topography and ice-stream velocity, thus providing further insight in the dynamics of the ice sheet (see Box 10 in chapter 6). Existing SAR systems have demonstrated a capability to derive velocity measurements of the surface even though they were not designed specifically for this purpose, and so while there are currently constraints on what can be achieved in terms of coverage and accuracy, the future utilization of SAR techniques is promising.

5.3.2.1 Systematic Ice Sheet Measurements

A key element of the NASA polar science strategy is the implementation of the ICEsat mission to measure changes in the elevation of the Greenland and Antarctic ice sheets. Observations from this mission will be used to evaluate changes in the surface mass budget and total ice volume, and to infer the contributions to sea level change (Box 9).

While the surface mass budget of ice sheets (snow accumulation, sublimation and/or melting) may vary with seasonal or interannual changes in polar climate, the ice dynamics varies over much longer time scales. ICEsat measurements of surface elevation are intended to provide the basis for an order of magnitude improvement in the accuracy of estimates of ice sheet mass balance and changes. The agency plans to repeat precision altimetric measurements at intervals of about 10 years, taking advantage of the increased accuracy that may accrue from on-going technical advances.

The agency has also, in collaboration with the Canadian Space Agency, demonstrated how powerful SAR data are in mapping the boundaries of the ice sheets and their surface dynamics, as well as in revealing surface features that were hitherto unknown (for example, giant snow “dune” fields). Repeated observations of the ice sheets by SAR, involving interferometric modes of observation that can be used for mapping surface ice dynamics, is a priority for NASA and will complement the altimeter missions.

5.3.2.2 Experimental Ice Sheet Measurements

Measurement of the ice sheet fluxes and mass balance depend on reliable estimates of ice sheet accumulation, ablation and dynamics. While there has been success in measuring surface dynamics and mapping areas of melt, snow accumulation rates over the ice sheets remain very uncertain. Effort will continue to develop methods for estimating surface accumulation rates from space.

Box 9
Precision Polar Altimetry Mission

The first precision altimetry mission, the Ice, Cloud and Land Elevation Satellite (ICESat) will be launched in July 2001 as part of the EOS program. ICESat will carry the Geoscience Laser Altimeter System (GLAS) and a GPS orbit determination system, to measure along-track ice sheet and land topography to an absolute accuracy of 10 cm or better, within a footprint of 70 m or less. The mission will also provide cloud profile information with 150m vertical resolution.

A repeat mission, focused on the primary science objective of measuring changes in the topography and mass balance of polar ice sheets, is planned in the 2010 time frame. The repeat mission may use a lidar altimeter similar to GLAS, or some other system that would enable precision altimetry measurements within a significant swath along the satellite track.

5.3.2.3 Field Measurement Campaigns and Ice-Sheet Process Models

NASA has played a leading role in supporting the application of airborne and field-based technology to studies of the Greenland Ice sheet, through the Program for Arctic Regional Climate Assessment (PARCA). Currently, surface-based and airborne measurements provide the only means to acquire certain critical ice sheet measurements, such as the depth and topography of the underlying terrain. Repeat airborne laser-altimeter surveys of the Greenland ice sheet have been conducted in 1998 and 1999 over the flight lines originally surveyed in 1993 and 1994. The laser altimeter technology allows areas of high relief to be surveyed, where highly dynamic outlet glaciers are often located. The repeat surveys provided the first clear indication of regional differences in ice sheet changes: conditions close to balance across the interior with some significant changes, predominantly thinning, around the margins.

Furthermore, NASA has supported the development of radar sounding techniques that are novel in being able to penetrate areas of “warm” ice that are close to pressure melting point, and hence has extended our knowledge of ice thickness to new regions of the ice sheet. NASA has also installed automatic weather stations on the Greenland ice sheet, to help interpret both aircraft and satellite data. It is foreseen that the acquisition of unprecedented high-precision ice topography, surface velocity and mass balance data will create a major body of information to support the modeling the ice sheets and glaciers. Prediction of future ice sheet changes requires that initial boundary conditions be known. Surface velocity as well as surface and basal topography are essential parameters that are needed for model initialization. NASA will provide these measurements through continued airborne (e.g. radar sounding) and spaceborne measurements. The NASA polar research program eventually aims to apply these techniques in conjunction with complementary NSF field measurements to key regions of the Antarctic ice sheet, as well as to other significant bodies of ice in the Arctic and sub-Arctic.

Field measurement campaigns are complemented by model studies of ice sheet processes and large-scale dynamics. The current focus of ice-sheet process modeling lies in understanding ice stream onsets and the sensitivity of the Antarctic ice sheet to ice shelf retreat. Full ice sheet models often do not adequately represent the dynamics of outlet glaciers and ice streams, which are the major source of ice discharge to the oceans. This can be partly attributed to the sparse measurements of key parameters (e.g. velocity and topography) with which to explore the physical processes that control ice flow. The stability of ice streams and the processes leading to their formation and maintenance, are critical in assessing the stability of the Greenland and Antarctic ice sheets as a whole. Ice streams are known to change significantly over periods of the order of a century; recent surveys carried out by NASA suggest that these features extend much further into the interior of the ice sheets than had previously been assumed. Ice shelves exert back-pressure on ice streams and have long been thought important to the overall stability of ice sheets, particularly the West Antarctic ice sheet. Both ice stream onsets and ice shelves remain priorities for modeling studies in tandem with observational campaigns.

5.4 LINKAGES

Linkages with other NASA Programs

The principal scientific linkage of Ocean and Ice research is with Global Water and Energy Cycle (GWEC) research activities outlined in Chapter 4. Altogether, the Ocean and Ice, GWEC, and the Earth System Observation and Modeling research themes (Chapters 4, 5, and 7) embrace the physics of the climate system. It is important to recognize that relatively small changes in mean climatological properties can induce marked changes in the frequency and/or strength of weather disturbances or sea level inundation: an essential requirement for practical application of climate prediction is the ability to link observed or predicted climate phenomena to significant regional weather and hydrologic events (Chapter 4). In addition, water mass formation links the global water cycle and climate to the slower oceanographic processes and freshwater transport in the ocean realizes the closure of the global water cycle on longer time scales.

The solid Earth and physical oceanography programs have a common interest in the measurement of the static and time-dependent components of the Earth's gravity field and contribute to understanding sea-level change (Chapter 6). A precise description of the geoid is required to infer relevant "dynamic height" gradients from relative topographic measurements obtained from altimetry satellites. In addition, measuring the variable component of the gravity field has the potential to provide global information about the ocean mass distribution (bottom pressure), water storage over continents or in aquifers, and the continental ice sheet mass balance. The precise measurement of the Earth's gravity field is the only remote sensing technique that does not rely on electromagnetic signals, and offers prospects for investigating the denser components of the Earth system.

The principal anthropogenic influence on climate is through changes in the cycling of carbon. The ocean is a vast buffer for atmospheric carbon dioxide and a sink for a significant fraction of the excess carbon dioxide flux generated by man's activities. The biogeochemical aspects of the oceanography program are addressed in Chapter 2, as well as the essential scientific linkage between ocean circulation dynamics and biogeochemistry. Important contributions to radiative forcing of the Earth climate also result from changes in the concentration and distribution of a wide range of chemically active trace gases (especially, ozone) and aerosols. Conversely, atmospheric transport and the chemical reactions that govern the distribution of trace gases are sensitive to the state of the atmospheric circulation and climate. The two-way interactions between atmospheric composition and climate are considered in Chapter 3.

Linkages with other US agencies

NASA's Ocean and Ice research is conducted in close coordination with other federal agencies participating in the US Global Change Research Program. This cooperation is particularly active in organizing the U.S. contribution to the study of Climate Variability and Predictability (international CLIVAR program). The Ocean and Ice research theme directly supports this major scientific initiative, also sponsored by NSF, NOAA, and the Department of Energy. Furthermore, NASA and NSF share a special interest in the analysis and synthesis of observations obtained by two major global oceanic research programs that are reaching completion, the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS).

Another strong link is developing between NASA, NOAA, Navy, and NSF to support and organize a Global Ocean Data Assimilation Experiment (GODAE) aiming to demonstrate the feasibility and operational value of global oceanography in the period 2003-2007. It is likely that this joint effort will develop as part of the National Oceanographic Partnership Program, and may extend to include new domains such as the polar oceans (where these agencies are already cooperating in support of the International Arctic Buoy Program). Cooperation is also developing with the Navy and the DOD/NOAA National Polar-orbiting Operational Environmental Satellite System (NPOESS) for the measurement of ocean surface wind. It is expected that joint wind measurement research will emerge from the Navy/NPOESS Coriolis (passive radiometry) and the NASA Seawinds (scatterometer) experimental programs. In addition, NSF will continue to be a key partner for ice sheet research, following successful partnership in Greenland with the PARCA experiment. It is anticipated that this collaboration will extend to Antarctic field campaigns.

International Linkages

The Ocean and Ice research theme is closely aligned with the scientific goals and scientific strategy of the Climate Variability and Predictability (CLIVAR) and Arctic Climate System Study (ACSYS) components of the international World Climate Research Program. It is directly relevant to international assessments of climate change and the formulation of climate change scenarios conducted for the Intergovernmental Panel on Global Change (IPCC). By tradition, oceanography and polar research have always been truly international in scope and strongly reliant on cooperation between research institutions in sea-going nations and partners in the exploration of the Antarctic continent. The NASA research on climate variability and prediction builds on this tradition, again demonstrated by WOCE achievements in the recent past. In addition, several major bilateral cooperative programs or projects are being pursued with foreign agency partners, notably France (with the joint realization of the TOPEX/Poseidon ocean topography mission launched in 1992, and follow-on Jason missions), Japan for ocean wind vector measurements (NSCAT on Japan's ADEOS mission in 1996-97 and Seawinds on ADEOS-2), and Canada for radar mapping of the Antarctic ice sheet and the Arctic ocean (RADARSAT).

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